

Influence of linearly polarized radiation on magnetoresistance in irradiated two-dimensional electron systems

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We study the influence of the polarization angle of linear radiation on the radiation-induced magnetoresistance oscillations in two-dimensional electron systems, and examine the polarization immunity on the temperature and quality of the sample. We have applied the radiation-driven electron orbits model obtaining that the magnetoresistance is affected by the orientation of the electric field of linearly polarized radiation when dealing with high quality samples and low temperatures. Yet, for lower quality samples and higher temperature we recover polarization immunity in the radiation driven magnetoresistance oscillations. This could be of interest for future photoelectronics in high quality mesoscopic devices.

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Important and unusual properties have been discovered when two-dimensional electron systems (2DES) are subjected to external AC or DC fields¹. We can highlight the recently measured effect of microwave-induced resistance oscillations (MIRO)^{2,3} and zero resistance states (ZRS)^{2,3}. They are obtained when two-dimensional electron systems, in high mobility samples at low temperature ($\sim 1K$), are subjected to a perpendicular magnetic field (B) and radiation (microwave (MW) band) simultaneously. In these experiments, for an increasing radiation power (P), one first obtains longitudinal magnetoresistance oscillations which evolve into zero resistance states at high enough P . Early experiments obtained similar MIRO when radiation is linearly polarized either in the transport direction or perpendicular to it⁵. A recent study utilizing a new setup has shown, however, a marked linear polarization sensitivity^{6,7}. Other experiments obtained that the magnetoresistivity response ρ_{xx} is independent of the direction of the circular polarization of radiation⁴. Some theoretical contributions⁸⁻¹⁴ have been presented trying to explain such striking effects but to date, there is no consensus on the physical origin. In this paper we present a theoretical model to treat the physical problem of a 2DES subjected simultaneously to a static, moderate and uniform magnetic field (B) and radiation^{8,15} linearly polarized at any angle. We study how the polarization immunity first detected in previous experiments can be altered when dealing with higher quality samples and lower temperatures. We propose that under such conditions, radiation-driven magnetoresistance can be affected depending on the different angles of linearly polarized radiation. The theory and results presented here are important to understand, more in deep, the coupling between matter and radiation and in the presence of static B and it could be of interest for the development of future photoelectronics in high quality mesoscopic devices.

We consider a 2DES ($x - y$ plane) subjected to a perpendicular (z direction), static B , a DC electric field E_{dc} , responsible of the electron transport through the sample (x direction). The system is also subjected to linearly polarized MW radiation. The electric field $\vec{E}(t)$ of MW can be in different polarization angles (α) (see Fig. 1). This field is given by: $\vec{E}(t) = (E_{0x} \vec{i} + E_{0y} \vec{j}) \cos wt$ where E_{0x} , E_{0y} are the amplitudes of the MW field and w the frequency. Thus, α is given by $\tan \alpha = \frac{E_{0y}}{E_{0x}}$. Considering the symmetric gauge for the vector potential of B , ($\vec{A}_B = -\frac{1}{2} \vec{r} \times \vec{B}$) the corresponding Hamiltonian reads:

$$H = \frac{P_x^2 + P_y^2}{2m^*} + \frac{w_c}{2} L_z + \frac{1}{2} m^* \left[\frac{w_c}{2} \right]^2 [(x - X)^2 + y^2]$$

$$\begin{aligned}
& -\frac{e^2 E_{dc}^2}{2m^* \left[\frac{w_c}{2}\right]^2} \\
& -eE_{0x}(x-X) \cos wt - eyE_{0y} \cos wt - eE_0 X \cos wt
\end{aligned} \tag{1}$$

$X = \frac{eE_{dc}}{m^*(w_c/2)^2}$ is the center of the orbit for the electron cycloidal motion, w_c is the cyclotron frequency, L_z is the z-component of the electron total angular momentum. Remarkably, the exact analytic solution of the Hamiltonian H can be obtained^{8,15}:

$$\Psi(x, y, t) \propto \phi_N [(x - X - a(t)), (y - b(t)), t] \tag{2}$$

where ϕ_N are the well-known Fock-Darwin states¹⁶. The most important result with a deep physical meaning is that, apart from phase factors, the wave function Ψ is proportional to a Fock-Darwin state where the guiding center of the 2D oscillator is displaced by $a(t)$ in the x direction and $b(t)$ in the y direction, i.e., describing an approximately circular motion in the $x-y$ plane. This motion is reflected in the x direction as harmonic oscillatory with the MW frequency w . The magnitude and nature of this displacement and its physical effects will depend on the type of the time-dependent force.

The expression for $a(t)$ and $b(t)$ can be obtained for a definite polarization angle of the MW electric field with respect to the x direction, α ,⁸:

$$a(t) = \frac{eE_0 \cos wt}{m^* \sqrt{\frac{w_c^2(w_c^2 - w^2)^2}{w^2 \cos^2 \alpha + w_c^2 \sin^2 \alpha} + \gamma^4}} = A \cos wt \tag{3}$$

$$b(t) = \frac{eE_0 \sin wt}{m^* \sqrt{\frac{w_c^2(w_c^2 - w^2)^2}{w^2 \cos^2 \alpha + w_c^2 \sin^2 \alpha} + \gamma^4}} \tag{4}$$

γ is a material and sample-dependent damping factor which dramatically affects the movement of the MW-driven electronic orbits¹⁷. Along with this movement interactions occur between electrons and lattice ions, yielding acoustic phonons and producing a damping effect in the back and forth electronic orbits motion. This parameter γ is going to play a crucial role in how the polarization angle affects the magnetoresistance. Now we introduce the scattering suffered by the electrons due to charged impurities randomly distributed in

the sample^{8,18}. Firstly we calculate the electron-charged impurity scattering rate $1/\tau$, and secondly we find the average effective distance advanced by the electron in every scattering jump: $\Delta X^{MW} = \Delta X^0 + A \cos w\tau$ where ΔX^0 is the effective distance advanced when there is no MW field present. Finally the longitudinal conductivity σ_{xx} can be calculated: $\sigma_{xx} \propto \int dE \frac{\Delta X^{MW}}{\tau}$, being E is the energy. To obtain ρ_{xx} we use the usual tensor relationships $\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2} \simeq \frac{\sigma_{xx}}{\sigma_{xy}^2}$, where $\sigma_{xy} \simeq \frac{n_i e}{B}$ and $\sigma_{xx} \ll \sigma_{xy}$.

According to our model, the ρ_{xx} response under MW excitation is governed by the term $A \cos w\tau$: $\rho_{xx} \propto A \cos w\tau$. Therefore we would expect different results of ρ_{xx} depending on the angle α since ρ_{xx} depends on α through the amplitude A (see equation 3). However if the damping factor γ is larger than the MW frequency, $\gamma > w$, γ would become the leading term in the denominator of A . In this situation, γ is able to quench the influence of the other terms. Therefore similar values are obtained for the amplitude of the orbit center for different α . For GaAs and typical experimental MW frequencies^{2,17,19}, a value for γ about $1 - 2 \times 10^{12} s^{-1}$ is enough to obtain a similar ρ_{xx} response irrespective of the value of α . In Fig.2 we show the calculated ρ_{xx} as a function of B for linearly polarized radiation and for different polarization angles. MW frequency $w = 90$ GHz. ρ_{xx} response is practically immune to the polarization angle, specially for B below cyclotron resonance (see vertical dashed line, Fig. 2a).

In the same way we would be able to obtain an entirely different scenario lowering the parameter γ and making the frequency term the leading part in the denominator of A . We have to remember that the polarization angle α is part of the frequency term in A and in this new scenario different values of α will be reflected in the frequency term and eventually in the obtained magnetoresistance. We have developed a microscopical model for γ ^{8,20} that summarizes the interaction of electron with lattice ions giving rise to acoustic phonons as:

$$\gamma = \frac{2\Xi^2 m^* k_B T}{v_s^2 \rho \pi \hbar^3} \times \begin{matrix} < z > \\ > z < \end{matrix}$$

$$\left\{ 1 + 2 \sum_{s=1}^{\infty} \exp \left[-\frac{\pi \Gamma s}{\hbar w_c} \right] \cos \left[\frac{2\pi s \hbar w_{ac}}{\hbar w_c} \right] \right\} \quad (5)$$

where Ξ is the acoustic deformation potential, ρ the mass density, k_B the Boltzman constant, T the temperature, v_s the sound velocity and $\langle z \rangle$ is the effective layer thickness. When the total sum inside brackets is carried out we obtain²¹ after some algebra:

$$\gamma = \frac{2\Xi^2 m^* k_B T}{v_s^2 \rho \pi \hbar^3 \langle z \rangle} \left(\frac{1 - e^{\frac{-\pi \Gamma}{\hbar w_c}}}{1 + e^{\frac{-\pi \Gamma}{\hbar w_c}}} \right) \quad (6)$$

The latter expression expresses the physical fact that for high quality samples the Landau level width gets smaller and in an inelastic scattering event (phonon emission) is increasingly difficult to find a final Landau state where to get to. Then, the term inside brackets decreases, when compared to a lower quality samples. In other words, for high quality samples, the damping parameter γ will decrease, making increasingly difficult the damping by acoustic phonon emission and the release of the absorbed energy to the lattice. Therefore, we have a *bottleneck effect* for the emission of acoustic phonons. On the other hand, γ is linear with T and the use of lower temperatures will make smaller the damping parameter too. Summarizing, the joint effect of high quality samples plus lower temperatures makes possible to reach a situation where the frequency term is more important than the damping term, ($\gamma < w$) making visible a clear effect of the polarization angle on the magnetoresistance. For GaAs high quality experimental parameters and $T < 1K$, we obtain that $\gamma \simeq 1 - 2 \times 10^{11} s^{-1}$. In Fig. 3 we present calculated magnetoresistivity as a function of B for linearly polarized radiation with polarization angles $\alpha = 0$ and $\alpha = 90$ regarding the transport direction (x direction). These results correspond to a scenario of high quality sample and lower temperature ($T = 0.7K$). We observe that the ρ_{xx} polarization immunity can be clearly altered in function of the angle. This theoretical results have been confirmed by recent experiments on linearly polarized MW-induced resistance oscillations^{6,7}. We consider that the results presented here are important to understand the coupling between matter and radiation when an static B is present and it could be of interest for the development of future photoelectronic mesoscopic devices.

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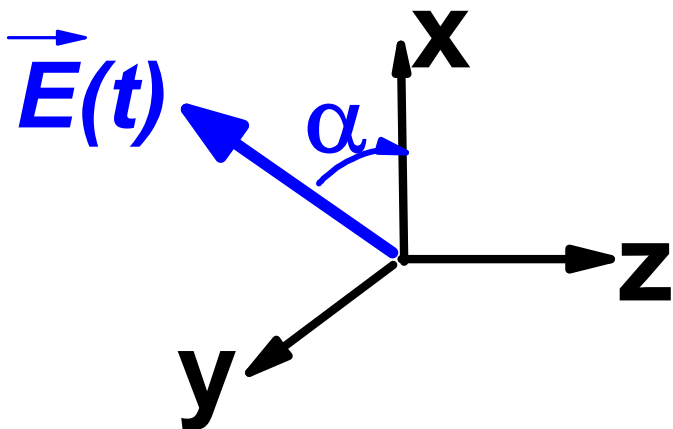
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Figure 1 caption: Schematic diagram showing a 2DEG illuminated by linearly polarized MW radiation at different polarization angles (α). a) $\alpha = 0$: the MW electric field, is aligned to the transport direction (x direction). \vec{E}_{dc} is the applied dc electric field responsible of the current. b) $0 < \alpha < \pi/2$. c) $\alpha = \pi/2$: the MW electric field is perpendicular to x .

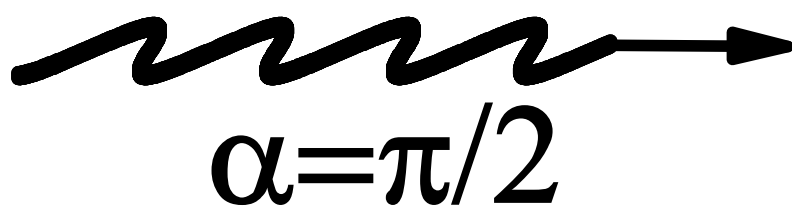
Figure 2 caption: a) a) Calculated magnetoresistivity ρ_{xx} as a function of B for linearly polarized radiation and different polarization angles α regarding the transport direction (x direction). In b) curves are shifted for clarity. In this scenario the damping parameter $\gamma > w$, then the ρ_{xx} polarization immunity can be clearly observed, especially for B below the cyclotron resonance (see vertical dashed line in the top panel). $T=1.5K$.

Figure 3 caption: Calculated magnetoresistivity ρ_{xx} as a function of B for linearly polarized radiation and polarization angles $\alpha = 0$ and $\alpha = 90$ regarding the transport direction (x direction). These results correspond to a scenario of high quality sample ($\gamma < w$), and lower temperature ($T = 0.7K$). We observe how the ρ_{xx} polarization immunity can be clearly altered in function of the angle.



MW

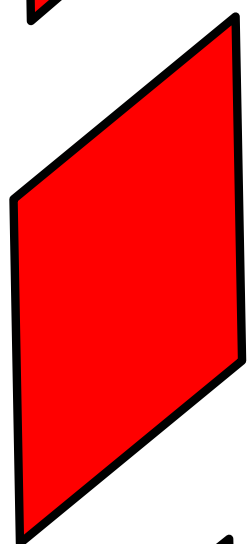
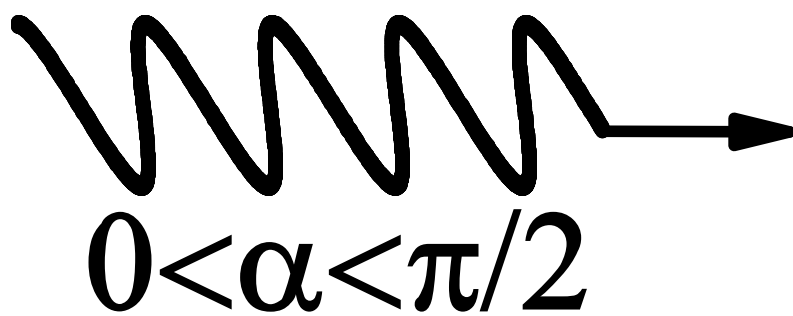
(c)



$\vec{E}_{dc}(X)$



(b)



(a)

